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FEASIBILITY OF UNITED STATES AIR FORCE FINITE ELEMENT MODEL CENTER
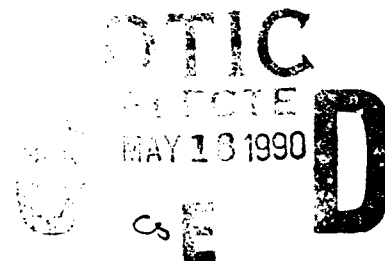
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August 1988

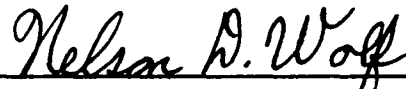Final Report for the Period July 1987 to January 1988

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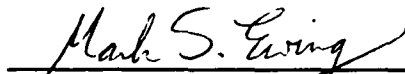This technical report has been reviewed and is approved for publication.

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The feasibility of establishing a centralized facility for acquiring, storing, and distributing finite element models used by the United States Air Force is investigated. Through contacts with potential finite element model users, the nature of usage within the technical community is characterized. The cost-effectiveness of servicing user needs through a centralized facility is investigated. The technical approach, software, and hardware for operating the center is studied. It is concluded that such a center would be feasible and cost-effective.

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Section 1
INTRODUCTION

1.1 Background

Finite element (FE) methods are widely recognized as the primary means of analyzing the structural integrity of aircraft. These methods evolved from rare uses in the mid-1960s to general usage in the 1970s to virtually universal usage in the 1980s; thus, the existence and completeness of FE models to confirm design adequacy for an existing aircraft is highly dependent on the aircraft vintage. However, the structural integrity of future aircraft can be expected to be supported by a rather complete hierarchy of FE models. At least the first generation of these models for a new aircraft is developed during the design phase of the aircraft life cycle. (K R) (

Under current practices, access by the United States Air Force (USAF) to these FE models is extremely limited. They are generally developed by the airframe designer (contractor) and delivery to the USAF is not required as part of the development contract. In cases where USAF organizations procure these FE models later in the aircraft life cycle, the cost is extremely high. This is partially because the models were originally developed for internal use by the contractor without the organization and documentation essential to external use, and partially because the USAF is in a poor negotiating posture. It may be in the contractor's best financial interest to discourage distribution of models outside the contractor organization.

Certain USAF organizations need FE models of aircraft to carry out their responsibilities. These needs range from investigating new derivatives of existing aircraft and evaluating modifications and repairs to supporting and validating technology development. The cost and manpower to develop comprehensive independent models is prohibitive. A mechanism is needed for the USAF to acquire and use contractor-developed FE models.

One way for the USAF to manage its requirements for FE models is through a centralized function that would operate a model repository. The objective of this Phase I SBIR study is to investigate the feasibility of organizing and operating such a finite element model center (FEMC).

1.2 Approach

The first step in studying whether and how an FEMC should be operated was to characterize the usage of FE models throughout the USAF. This was accomplished through a written survey, selected site visits, and telephone calls to gather information directly from potential users of data from the FEMC.

From the collection of information from users and discussions with the project sponsors, alternative concepts for the FEMC organization and operation were developed. These alternatives were analyzed and compared with each other with respect to how well they satisfied the needs of the user community. Once a preferred, or baseline, concept was selected, some details of its implementation were investigated. This included consideration of personnel, software and database structure, hardware, operation, and security.

Potential benefits and costs of the FEMC to the USAF were explored and compared with the benefits and costs of current practices. Complicating factors and difficulties in estimating the financial impact associated with improved fleet performance and reliability resulted in a more qualitative than quantitative assessment.

A plan for further study and pilot implementation of the FEMC was developed. Execution of this plan is suitable for a Phase II SBIR contract award.

Finally, concise listings of conclusions and recommendations were developed.

Section 2
CHARACTERIZATION OF FINITE ELEMENT MODEL USAGE

Ultimately, the success of a USAF finite element model center (FEMC) will depend on how well it serves its users. Much of the funding to operate the center is likely to come either directly from these users or upon their recommendations. Therefore, interaction with the potential users was an essential step in studying the feasibility of an FEMC. Only these users could provide sufficient details to permit an accurate characterization of FE model usage. A systematic approach was adopted to acquire information from the users. This consisted of a written survey, selected site visits, and telephone discussions.

2.1 Survey Development

Experience has shown [1] that simplicity is important in scientific surveys. Simplicity encourages a higher percentage of responses, avoids misinterpretations of the questions, and allows straightforward analysis of the results. A simple survey questionnaire was sent to a list of potential FEMC users; the list was provided by the project engineer (Dr. Vipperla B. Venkayya, AFWAL/FIBRA). This survey was designed to elicit basic information on user identification, aircraft identification, type of FE models (e.g., static, dynamic), source of the models, software used, hardware used, and uses of the models. An opportunity was provided for the respondents to characterize desired future usage as well as current usage.

2.2 Survey Responses

A survey response was received from every organization that was sent a questionnaire. This is highly unusual in scientific surveys and, it is to be hoped, is indicative of high interest in the prospect of establishing an FEMC. In most cases, several responses were received from each organization or closely-associated sister organizations.

Some usage features were extracted from the survey responses and are reflected in Tables 2.1, 2.2, and 2.3. Some judgment, rather than a simple counting, was used in making the tabulations shown. Each entry in the Tables is intended to

reflect a count of relatively independent entities that make use of FE models. For example, two responses from the same individual, one for static analysis and one for damage tolerance analysis (DTA), which both reflected VAX 785 computer usage, would be counted only once in the usage column. Similar judgments were applied throughout the tabulations.

Table 2.1

FINITE ELEMENT MODEL USAGE PATTERNS
(Number of Respondents from Survey)

FE Models	Current Usage	Desired Usage*
Static Analysis		
Stress or Internal Loads	14	2
DTA	8	
Dynamic Analysis		
Normal Modes	2	1
Complex Eigenvalue		
Frequency Response		
Transient Response	1	
Random Response		
Aeroelastic Analysis	2	2
(Aerodynamic)	1	
Heat Transfer Analysis	1	
Acoustic Cavity Analysis		

*Tabulated only if in addition to current usage

Table 2.2

COMPUTER PROGRAM USAGE
(Number of Respondents from Survey)

Computer Program	Current Usage	Desired Usage*
COSMIC NASTRAN	9	2
MSC NASTRAN	15	3
ASTROS	2	
UGO	1	
GIFTS	1	
IDEAS	2	
CDMS**	1	
TEAM, Eagle **		
FACES	1	
PATRAN	1	2
SUPERTAB	5	

*   Tabulated only if in addition to current usage

**   Aerodynamic (Panel) analysis

Table 2.3

COMPUTER USAGE
(Number of Respondents from Survey)

Computer	Current Usage	Desired Usage*
MICRO VAX II		4
VAX 11/750, 780, 785	14	
VAX 8650, 8800		2
CYBER	12	
CRAY		3
PS 390	1	
IBM PC		1
HP 350		1
TEK 4107, 4109	1	
Workstation TBD		1

* Tabulated only if in addition to current usage

Table 2.1 reflects the types of FE models being used by respondents. It is clear that stress or internal loads and DTA dominate the usage, but other model types are significant. Table 2.2 shows that NASTRAN dominates computer program usage, with MSC used somewhat more than COSMIC NASTRAN. SUPERTAB is the program of choice for pre- and post-processing. From Table 2.3, VAX computers are heavily used (this is especially true at the Air Logistic Centers (ALCs)), and CYBER usage is also prominent. Desired future usage of CRAYs is significant enough to influence whatever decisions are impacted by computer type.

The desired usage for types of FE models reflects little intention on the part of respondents to do types of analyses that they are not already doing. Desired computer usage generally reflects upgrades to larger capacity in similar equipment. Similarly, great changes did not appear to be anticipated in the computer programs to

be used in the future. This apparent stability, if real, has the important implications that an FEMC as planned today would be serviceable for the foreseeable future.

Another overall observation is that virtually no dynamic modeling is being done, nor is it anticipated in the future, by the ALCs. Most of the interest in dynamic modeling appears to be at Wright Patterson AFB. On the other hand, interest in stress analysis, and especially DTA, is very high at the ALCs.

2.3 On-Site Visits and Follow-up Discussions

For reasons stated previously, the written survey was kept quite simple. A more comprehensive evaluation of some issues and exploration of more qualitative matters could best be accomplished by face-to-face discussions. For this reason, several organizations were visited and others telephoned to obtain additional information. These follow-up discussions should be regarded as a sampling of some opinions that may not reflect the views of the user community as a whole. However, some attempt was made to focus these follow-up discussions on organizations that are particularly active in FE analysis.

The discussions were much more free-form than the written survey and were allowed to wander to topics other than those preplanned. However, the questions below are typical of those that were explored:

What has been the motivation for acquiring the FE models that you have procured from contractors?

What is the source of funding for their procurement? What information is available on the cost of acquiring these models for USAF use?

What are your reasons for using the particular computer programs that you use? What are your thoughts on COSMIC vs. MSC NASTRAN?

Would the kinds of models you acquire be likely to be available from an FEMC?

Would the kinds of models that you develop be likely to be useful to others through an FEMC?

Answers to these kinds of questions were diverse, but with some useful trends. The trends summarized below by no means reflect a uniform response.

Models are seldom acquired to be used "as is." Some modification, refinement, or at least the addition of new load cases is usually intended. The FEMC would need to provide complete detail for most models to suit the users' purposes.

Funding for models is usually from the users' immediate parent organization. Or, perhaps more accurately, the immediate parent can decide whether to use available funds to acquire a user-desired model or for some different purpose. Assuming that completely separate funds would not be available to operate the FEMC, user organizations would need to be convinced that "value for their money" is being received by acquiring models through the FEMC.

The cost of acquiring FE models from contractors was not easy to ascertain. However, the order of magnitude of such acquisitions is reasonably characterized. A single model for a particular purpose can run to the high tens of thousands or low hundreds of thousands of dollars. Acquisition of several models for a particular system to support an aggressive DTA, for example, can run from several hundred thousand to the low millions of dollars. A well-run FEMC could probably reduce these costs substantially. This will be discussed further in later sections.

Most users seem "married" to the FE programs and pre/post-processors they are now using. In particular, users of MSC NASTRAN would typically regard a change to COSMIC NASTRAN as a significant regression. There is some prospect that expected improvements in COSMIC NASTRAN could change this outlook.

Most users believe that the kinds of models they acquire from contractors would likely be available in a well-structured FEMC. However, most believe that the models that they develop internally are for such special purposes that they would rarely be of any value to other organizations.

Numerous other valuable insights were developed through these interactions with potential users. They are of a more subtle nature, but influence the planning discussed in later sections.

The nature of FE model usage in the USAF appears to be stable in its scope, but growing in the breadth of organizations involved. For example, the San Antonio

and Oklahoma City ALCs appear to be on a track of hardware and software acquisition that could move them substantially toward the more extensive stress and DTA analysis capabilities currently existing at the Warner Robins and Sacramento ALCs.

Unlike the situation experienced with older vintage aircraft, development of new systems is certain to include a comprehensive array of FE models developed by the airframe contractor. When coupled with the increasing user capabilities within the USAF, this fact calls for the USAF to seriously consider the most effective way to exploit the changing environment.

Section 3
DEVELOPMENT OF CANDIDATE FEMC CONCEPTS

There is a broad range of workable structures for an FEMC. It is important to develop an approach that is not only workable, but somewhere near optimum in terms of utility and cost-effectiveness. There are numerous common factors to any approach (such as a good standard of specification for new FE models). The major variable appears to be the degree of centralization of the function. Therefore, three alternative degrees of centralization will be evaluated, and one of these will be selected as a baseline. The baseline will then serve as a framework for exploring and developing other issues regarding implementation. Some common features of all concepts will be discussed in Section 3.1. Only the differences between centralization concepts will be emphasized in Sections 3.2, 3.3, and 3.4.

3.1 Commonality Among Concepts

In all concepts, the FEMC would be responsible for development and control of the standards to be used in acquiring FE models. It would be responsible for advising the Systems Project Office (SPO) during the contractor selection and design phases to help ensure a negotiated arrangement advantageous to the USAF. It would be the focal point for taking delivery of models to be used for evaluation during design reviews. The structure during the system procurement and design phase would be the same for all concepts, and is illustrated in Figure 3.1.

The FEMC would also be responsible for developing or acquiring the technology needed for its efficient operation. This would include development of computer-program-to-computer-program translators, the database scheme for storing and retrieving models, and methods to combine several models into one and to extract boundary conditions from a global model for application to a local model.

For all concepts, the FEMC would maintain a complete (electronic) catalog of all USAF aircraft FE models (1) acquired from contractors, (2) known to exist at the contractors' facilities, or (3) developed by the USAF user community.
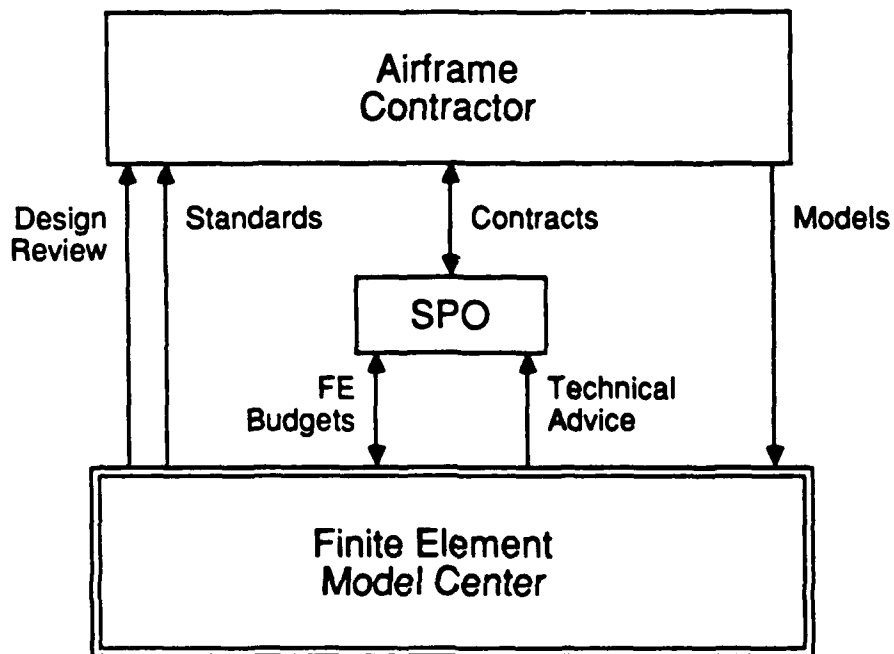
3 - 1

**Figure 3.1. FEMC Relationships During Procurement
and Design Phase**
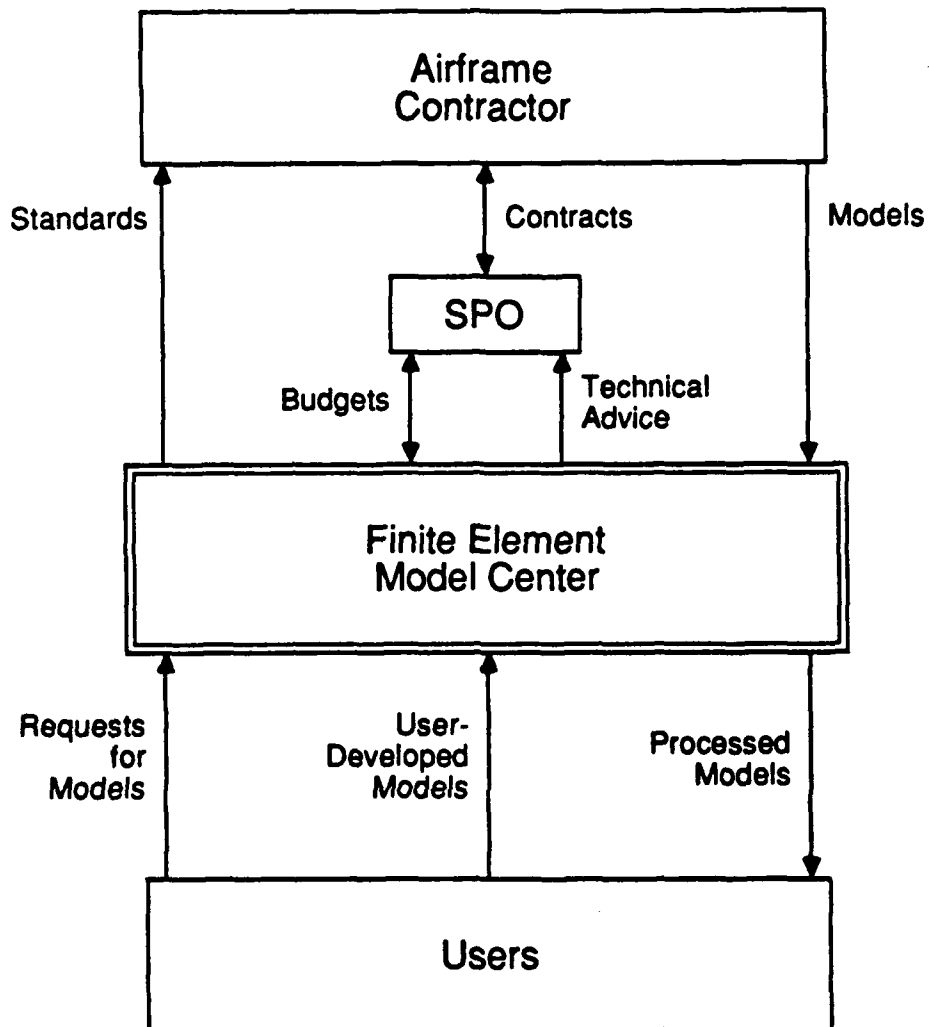
3.2 Centralized Concept

In this concept (see Figure 3.2), the FEMC would be the focal point for the flow of all models between the airframe contractor and the user throughout the aircraft life cycle. The FEMC would also be involved in the budgeting process to assist the SPO in prioritizing requests from various users.

An advantage of this concept is that a high degree of commonality and consistency between the FE models for the various USAF systems would eventually evolve. The concomitant disadvantage is that users would have less control over models acquired for their needs than they have at present or would have under the decentralized or network concepts. The substantial involvement of the FEMC in budgeting and policy matters would imply a greater need for USAF civil service or military personnel day-to-day involvement than would be true for a decentralized concept.

3.3 Decentralized Concept

In the decentralized concept illustrated in Figure 3.3, the FEMC would be totally a service organization, with little control of the model acquisition process once the operational phase of the system life cycle begins. Such controls would pass to the users who would make the decisions on their required models, budgets, and which models are suitable for inclusion in the repository.

An advantage of this concept is that it is the least disruptive to current practices while still adding some extremely important advantages. These include acquiring the models developed during the procurement and design phase, acting as an exchange for models acquired during the operational phase, and generally enhancing the utility of USAF aircraft FE models. Some commonality among models would probably result, but not to the same extent as with the centralized concept.

**Figure 3.2. Centralized FEMC Concept
(Operational Phase)**
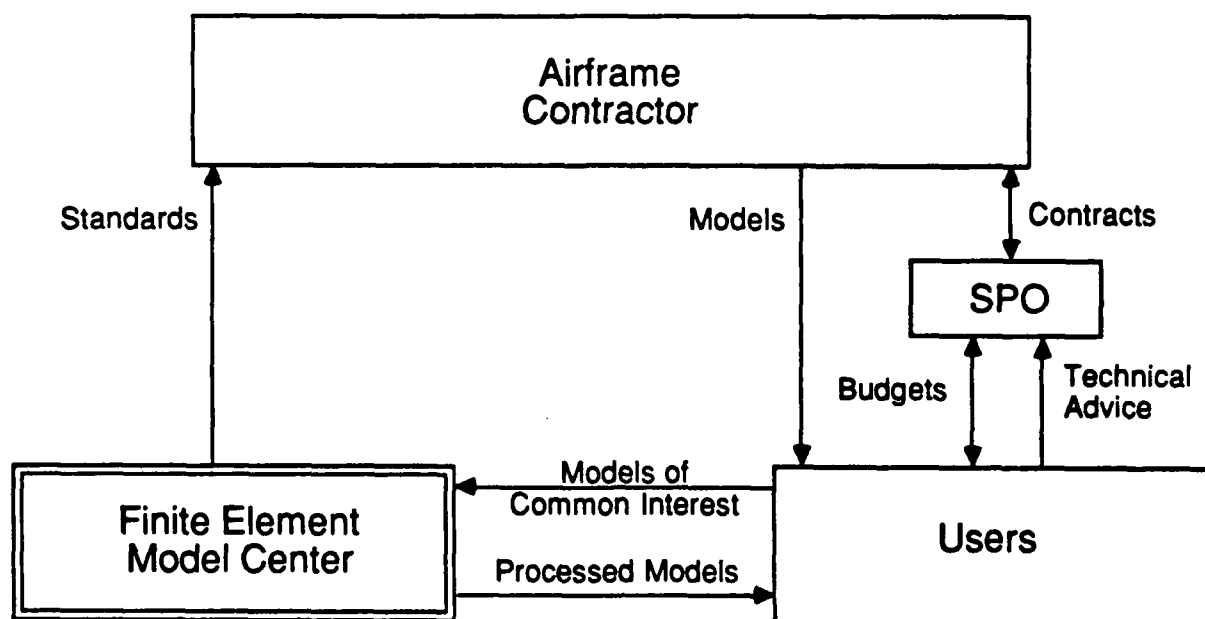
**Figure 3.3. Decentralized FEMC Concept
(Operational Phase)**

3.4 Network Concept

The network concept, as illustrated in Figure 3.4, is a marriage of the centralized and decentralized concepts, designed to capture most of the advantages of each. Since global (i.e., complete airframe) models are likely to be needed by multiple users, these would be acquired by the FEMC as in the centralized concept. These would likely be updated to the models acquired by the FEMC during the procurement and design phase. Considerable commonality among different systems should eventually evolve for these global models.

Special purpose models would be acquired by the users, but the FEMC would have a voice in deciding whether they are of enough common interest to be stored in the repository. Both the FEMC and the users would be involved in the budgeting for FE model needs.

An advantage of the network concept is that it allows each organization some control in the area in which it is strongest. The major disadvantage is that the crisp lines of responsibility and authority are not tightly defined. The SPO would need to take an active role in assessing conflicting needs.

3.5 Tentative Concept Selection

Because it represents a compromise between two extremes, and because something like the network concept is thought to be most likely to eventually prevail, the network concept has been selected as a baseline for further development in Section 4. In fact, much of the implementation outlined in that section would be common to all three concepts.
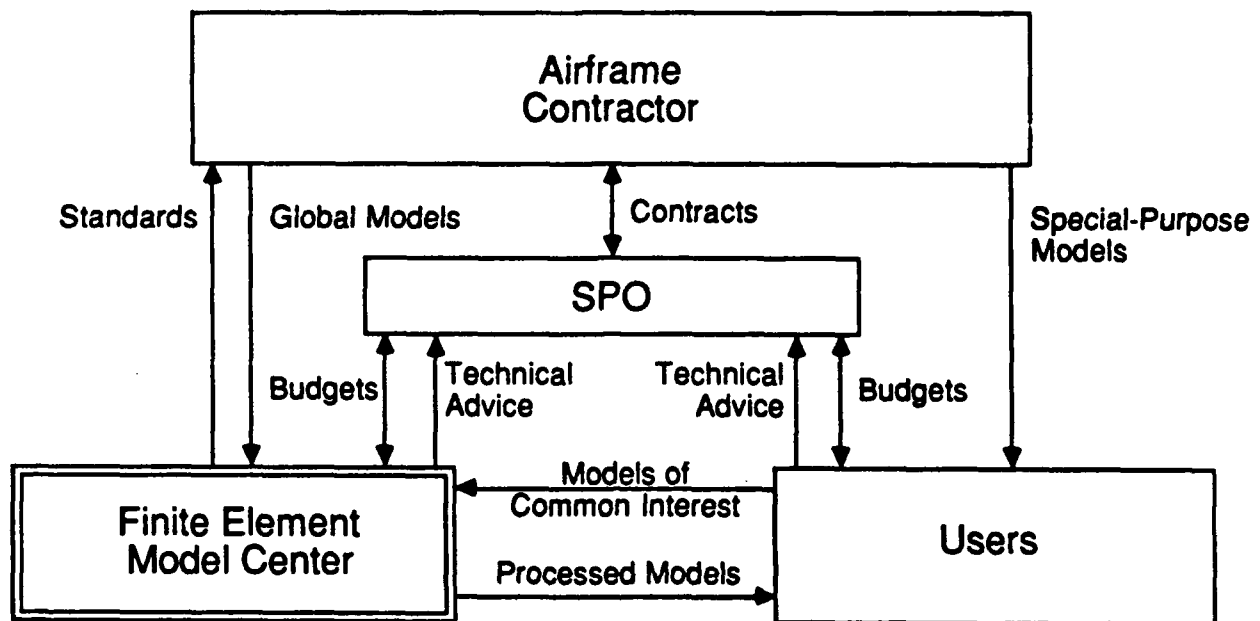
Figure 3.4. Network FEMC Concept (Operational Phase)

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Section 4
IMPLEMENTATION OF THE NETWORK CONCEPT

Several aspects of FEMC implementation deserve some study and comment during the current project. These include some consideration of the number and type of personnel, the database (and associated software) required for storage and retrieval of models, possible computer hardware, operation of the center, and security of the models from unauthorized disclosure. These implementation issues will be addressed in this section.

4.1 Personnel

It is envisioned that the FEMC will be operated by a contractor under close guidance of the USAF. The center cannot be successful unless properly staffed. The staff providing day-to-day contact with users must be regarded as technical peers by the most knowledgeable users. This means that there must be a core staff of experienced engineers with graduate degrees to provide the basic services. For planning purposes, a staff of two such engineers is envisioned. In addition, a contractor FEMC manager of national stature in finite elements, preferably at the Ph.D. level, is essential. The USAF project engineer assigned to monitor the contractor effort should have similar credentials. The engineering staff should be provided approximately two programmer/technicians, one secretary, and one clerical assistant. The support level should be such that essentially no engineering time is spent accomplishing tasks that could be assigned to support staff.

4.2 Software and Database Structure

The center needs software to service three functions:

1. FE analysis
2. Pre- and post-processing of finite element models
3. FE model information database entry and query.

These items will be discussed in more detail below.

Finite Element Analysis Software

Several decisions must be made with regard to FE analysis software. Should the FEMC require models to be delivered in a specified format? If so, what format? What software should the FEMC use to validate models? Should the FEMC distribute models only in the delivered format?

These questions will be addressed in reverse order, since it seems appropriate to start with the end user whose need is the basis for development of the proposed repository. The survey suggests that the most widely used program among potential users of the FEMC is MSC NASTRAN. COSMIC NASTRAN comes in second. Because MSC NASTRAN has greater capabilities than, and is perceived to be easier to use than, COSMIC NASTRAN, it is unlikely that MSC users will be willing to switch. Since both programs are undergoing continued development, it is also unlikely that COSMIC's version will catch up with MSC's. An even greater diversification of FE program use is likely as FE modeling becomes more widespread and greater use is made of nonlinear and optimization capabilities. The list of candidate programs may look like:

> COSMIC NASTRAN
> MSC NASTRAN
> ABAQUS
> ADINA
> ANSYS
> ASTROS
> MARC

Thus, the FEMC should consider expanding its services to provide models translated into the format requested by the USAF user. This may be necessary to gain the support of the repository's potential user community.

The FE software to be used by the FEMC staff is a free choice. One software package may be used even if translations to other programs are provided by the FEMC. COSMIC NASTRAN may be an attractive choice because it is low in cost and yet maintains substantial commonality with end users.

If a model translation capability exists at the FEMC, the FEMC could offer a choice of several standard formats for delivery of the models by the airframe manufacturer in compliance with the CDRL. This list would still probably be a subset of the above list of FE codes. It could potentially ease the burden on the manufacturer, thus reducing the cost to the USAF. This is particularly the case when an analysis feature is used by the manufacturer that is not supported by COSMIC NASTRAN. Manufacturers may, of course, be using in-house codes, but these are often specialty versions of other codes.

Pre- and Post-Processing Software

Pre- and post-processing software is required for efficient FE modeling. This software will be required by the repository staff during checkout and validation of models it receives.

Four candidate programs are suggested: PATRAN, SUPERTAB, Intergraph, and NAVGRAPH. All these programs have a wide range of options that make them suitable from a capability standpoint. NAVGRAPH is a new product that has been sponsored by the Department of the Navy. Thus, it has the advantage of being available to the USAF without a license fee. However, it has the disadvantages of being new and having rather uncertain support. Intergraph's product is now available on workstations other than Intergraph's own hardware, so that it is now more portable. However, it is not currently used by any of the repository's user community. PATRAN and SUPERTAB become the most likely choices. SUPERTAB currently has two advantages. First, it has the widest current use, based on the survey data. Second, it has a CAD capability. It should be pointed out that commonality of pre- and post-processing software between the FEMC and the FEMC's users is not necessary, and is less important that commonality with the FE programs themselves. CAD capabilities are not likely to be important in the near term, but may become more important as the FEMC expands its role to collect and store a greater volume of design-related data.

Most pre- and post-processing software provide translators in order to support a range of FE modeling programs. This mechanism could be used to translate incoming models to COSMIC NASTRAN, and to translate outgoing models to the user's specified format, such as MSC NASTRAN.

Database Software and Structure

Data on FE models consists of the following:

1. Information about the type of model and its purpose

2. Detailed explanation of modeling assumptions, including drawings of the part

3. The FE model

4. Results of the FE analysis

The FEMC should consider keeping only the first of these on-line. This information is sufficient for a user querying the database to decide whether or not to request the model. The delay of a week in routine operations or overnight in emergencies in obtaining the necessary clearances and receiving the model through the mail is not likely to impact operations at an ALC or ASC.

The second item above would be difficult to store on-line because of its graphical nature. The final item could represent large volumes of data depending upon to what extent it is summarized. Finally, keeping the last three items off-line will greatly ease security concerns, which are explained in more detail in Section 4.5.

The information about the type of model and its purpose could contain a list of attributes to be used in the search process. These attributes could include:

- aircraft name (e.g., F-111)
- aircraft type
- aircraft component or assembly (e.g., wing)
- analysis type (e.g., dynamic)
- analysis subtype (e.g., normal modes)
- analysis date
- analysis performed by
- FE program used (e.g., MSC NASTRAN)
- storage location (e.g., repository)
- validated by repository (e.g., yes).

An abstract would also be included in the database, which would describe the model and its purpose in more detail.

This procedure would allow a user to search the database using logical constructs with commands like:

find name = F-11 and component = WING

find (name = F-15 or name = F-16) and type = DYNAMIC.

The database program would then inform the user of the number of entities found that match the search. The attributes of these entities could be reviewed to further refine the search. Finally, complete abstracts of promising models could be reviewed on-line, leading to a decision by the user to request or not request the model.

A number of software products are available to operate such a database. Some of these products allow for full text search of the abstract (in addition to the attributes search described above). Database programs include DATATRIEVE, ORACLE, RDBS, SPIRES, and STAIRS. The final choice of this software may be based upon cost and hardware compatibility considerations. The planned database is relatively simple and small, so that a wide range of software products are available to support it.

4.3 Hardware

The hardware configuration is chosen based on the anticipated usage and type of software to be used. This requires that the software be available for the chosen system, and that the anticipated usage will allow adequate response time for users. Constraints on the choice of hardware that are imposed include cost, security concerns, ease of use, and expansion capability.

A schematic of the repository hardware is shown in Figure 4-1, and includes the following hardware:

- A Host Computer - The host computer is the machine that dial-in users access. This machine is used to run the database software for both query by external users and update by internal users. The system may also be used by internal users for FE applications, including analysis and pre- and post-processing.

- Work Stations - Two workstations are envisioned, one for each engineer on the repository staff. The workstation could be set up to run all FE pre- and post-processing, as well as analysis, locally. In this case, powerful workstations would be required, with a less powerful host computer. Alternatively, the workstation could be used for just pre- and post-processing, with the analysis run on the host computer. Finally, the workstation could be reduced to a color graphics terminal, with all processing and analysis performed on the host. Here a much more powerful host computer would be required.

- Terminals - Two additional terminals are planned for use by other staff members to update the database and maintain the system.

- Disk Drives - Disk storage space is required for three functions. First, system and application software must be on-line. Second, the FE model information database must be kept on disk. Third, disk space for validation of FE models must be available. The disk for FE working storage is shown attached to the network, rather than the host, in Figure 4-1. This enables the workstations to access the FE data without interrupting the host computer.

- Tape Drives - Two tape drives are proposed. Tape drives are required for importing FE models for validation, backing up the disk storage, and copying tapes for transmittal to end users. Efficient tape copying requires two tape drives.

- Modems - Modems are required to support the anticipated volume of dial-in users.

- A Printer and Plotter - Hardcopy output devices are required for FE validation and other FEMC operational purposes.

- A Network - The network is recommended if computing power is distributed between a host and workstations. The network allows sharing of computational resources and system peripherals.

Specific machines will not be recommended in this report. However, some feel for size can be made based on rough estimates of FEMC activity. The FEMC computer activity is divided into two main types:

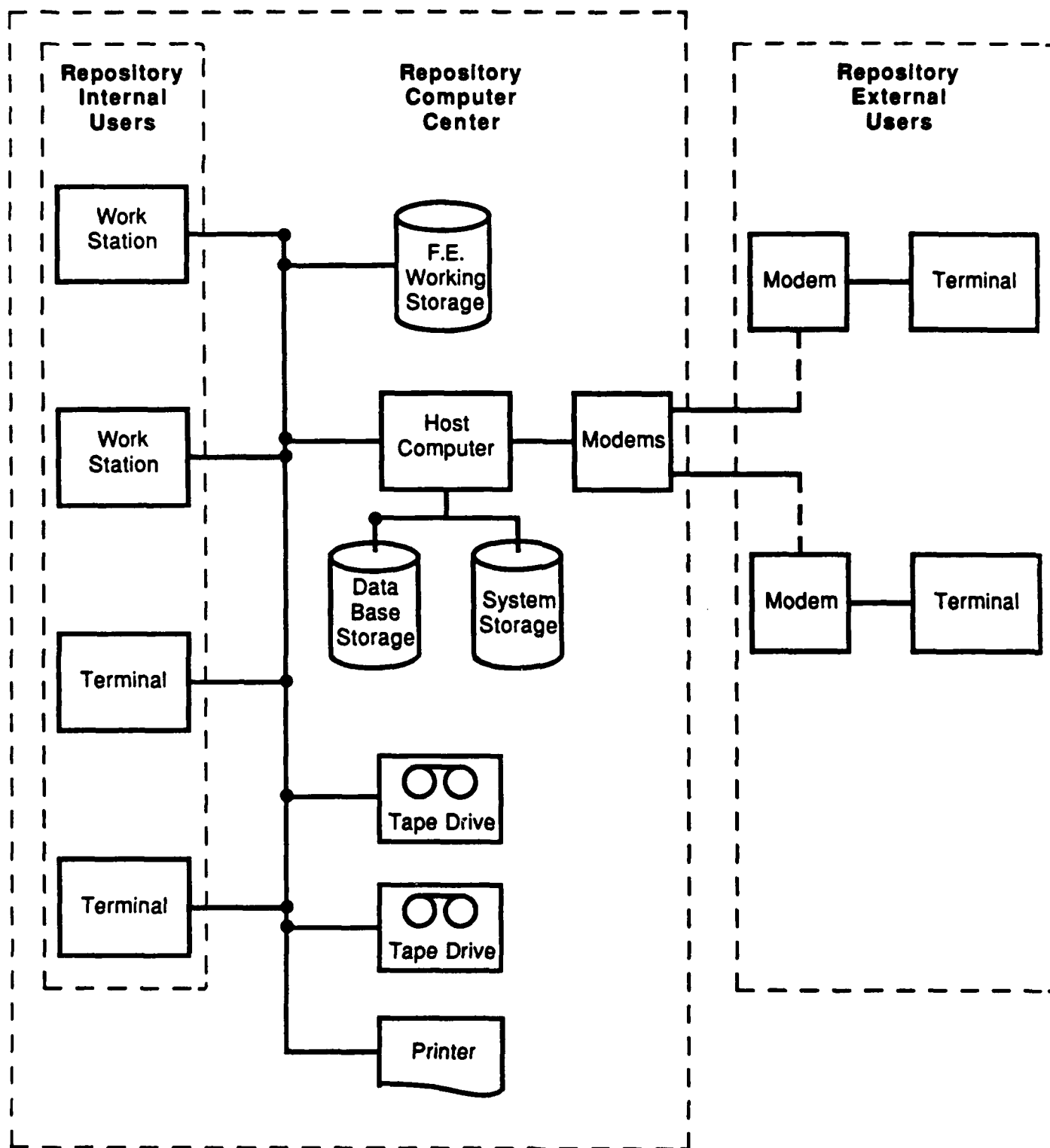1. Database storage, update, and query
2. FE model validation.

Figure 4.1. Schematic of Repository Hardware

The database might contain approximately 100 models within a year of operation. Within a period of three to five years, this might grow to 1000 models, with increasing use of FE models on new aircraft designs. Assuming that the database description of each model (not including the model itself) is less than three pages long, each model might require 10,000 bytes of storage, so that even allowing for a factor of three in storage efficiency in a database program, the size of the database would only be 30 megabytes. This is a small amount of storage in computer terms, and would require only a small portion of a typical disk drive.

Dial-in users to the database are expected to range from a few per day to a few per week. The cost savings to the USAF of several hundred thousand dollars per successful receipt of a model from the repository does not require a high volume of FEMC use to justify its existence. The combination of a low volume of queries and a small database indicates that the host computer can be sized at the low end of the spectrum for this function.

Storage requirements for validating FE models can be quite large by comparison. It is not uncommon to keep a 512 megabyte scratch disk available for running large FE models.

The larger FE models may have been run by the original model developers on high-end machines, including CRAY and IBM 3090 computers. Thus, the FEMC will need machines with sufficient computer speed and capacity. Because high throughput is not essential, workstations with high MIPS and virtual memory may be the most cost-effective approach.

It is clear that FEMC computational capacity is driven by the requirements of the FE validation process, and not by the size and demands of the database itself.

4.4 Operation

The operation of the FE repository under the network concept requires a shared responsibility between repository staff, and ALC and ASC staff. The repository staff have three primary functions:

1. Update the database

2. Distribute FE models

3. Validate FE models.

These three items are discussed in more detail below.

The FE model information database is updated upon receipt of a model from a contractor complying with a CDRL (see Appendix B), or upon receipt of information about a model which has been developed or modified by a ALC or ASC (see Appendix D). In both cases, the database can be updated immediately based on the information supplied, and the model would be labeled "not validated." In the case of the former, this label may be changed after successful validation. For the latter case, the validation label would remain unchanged and the model would be retained by the center that developed or modified it. This approach avoids costly validation of models that are likely to be used only once, but which merit being included in the database just in case they are needed again.

FE models are distributed by the repository staff to end users based on requests that contain an approved demonstrated need-to-know. The distribution requires that the tapes containing the FE model data and results are copied for transmittal to the requestor. Drawings and explanations of the model, loading, and other assumptions would also be copied for this purpose.

The repository staff would also be responsible for validating the FE models that it stores. The validation process will ensure that the data has been provided to the USAF in compliance with the CDRL. Indeed, the FEMC would probably be responsible for certifying that this is the case to the SPO. However, the validation process serves two further functions. First, it provides a check on the manufacturer's analysis approach and assumptions. Second, it validates the models for future use by the USAF.

The scope of the FEMC's activities could be expanded to include:

1. Translating models for compatibility with end users desired FE program

2. Modifying existing models as a service to users

3. Developing new models as a service to other centers

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4. Applying new models to evaluate proposed designs or design changes.

Other centers, such as ALC and ASC centers, developing or modifying models have the following responsibilities:

1. Inform the repository of new or modified models so that the database can be updated

2. Retain these models for possible further use

3. Distribute models, if requested.

A potential user at an ALC or ASC center, with an existing computer account at the repository, would follow the following procedure to obtain a model:

1. Access database through a terminal and modem

2. Identify possible model by searching model attributes

3. Review abstract for a more detailed explanation of the model

4. Demonstrate a need-to-know

5. Request model delivery from repository.

4.5 Security

Valuable information on the design of, and analysis methods for, USAF aircraft are contained in FE models. Thus, it is essential that security measures at the repository prevent access to these models from unauthorized persons, companies, or countries. The need for strict security will become even greater as FE models become more widely used on new projects, such as the National Aerospace Plane, ATF, and ATB.

As discussed earlier, the repository can fulfill its goals without actually keeping the FE models on-line. This approach provides the best form of security for the most valuable information--the finite element model. Information that describes the model in sufficient detail so that a user of the database can decide whether or not to request the

model must be kept on-line for functional efficiency. This information, although less sensitive, must also be kept secure.

Since access to the system is over telephone lines and through modems, specific measures need to be taken to prevent unauthorized dial-up users. Three steps can be taken to enhance security. First, no logo message should appear after a potential user dials the correct number. Second, a system password, in addition to the user password, should be required to proceed further. Third, a system call-back utility should be installed. This utility will call back a user who has correctly entered the system password, a user account, and a user password. Thus, the user must access the repository computer from a pre-approved telephone number.

Once a user has accessed the repository computer, further need-to-know based security can be enforced through file protection. For example, perhaps all model information relating to the National Aerospace Plane should be restricted to one AFLC. This restriction could easily be imposed by using, for example, access control lists (ACL) on a VAX computer.

The suggested schematic of repository hardware includes a network connecting the two workstations to the host computers. Because it is difficult to control security on a network, the dial-in users connect directly to the host and would not have privileges to access the workstations. This allows FE models to be processed by the repository staff without a compromise in security.

The repository computer should keep an audit trace of all database query sessions. This will provide useful information on usage of the center in addition to providing data for a security audit.

The actual transmittal of an FE model would take place only after a written request with a demonstrated need-to-know had been approved by the security officer of the repository. The required computer tapes and accompanying drawings and explanation could be transmitted in accordance with current regulations for classified documents.

In summary, FE model data can be kept secure by using the following measures:

1. FE models are separated from the database

2. Allocation of user accounts is controlled by the FEMC

3. A call-back system is installed for dial-in security

4. The database is segmented based on a need-to-know

5. An audit trace is kept of all computer query sessions

6. Transmittal of an FE model requires approval of a demonstrated need-to-know.

Section 5
POTENTIAL BENEFITS TO THE USAF

The time has come when certain USAF technical organizations can no longer provide state-of-the-art support to USAF systems without either acquiring contractor FE models or duplicating the contractor models in-house. Without such models, the work product of these organizations, which typically influences decisions affecting safety of operating aircraft, will be inferior to what is readily achievable. Independent development of duplicate models would be prohibitively expensive. Thus, the question becomes not whether it is advisable to acquire the contractor models, but how they should be acquired. The FEMC appears to be a reasonable mechanism to accomplish this. There may be other approaches, but many of the same features would be needed. The basis for the foregoing assertions is outlined in this section.

5.1 Summary of Current FE Model Usage

A number of USAF activities make use of FE models. This encompasses evaluation of repair and maintenance issues, which includes DTA as a subset. New derivatives of existing aircraft are also analyzed, as are modifications to incorporate aircraft enhancements or new weapons systems. Models are also used to validate analyses that have been performed by the contractor. Finally, these "real-world" models are an essential ingredient in validating new analysis technology as its development is completed.

For these purposes, certain USAF organizations now acquire contractor-developed FE models on a sporadic basis. There is little assurance that models will be available at the time they are needed; a wait of several months is not unusual. Often the needed models are never obtained, which can compromise the fidelity of whatever evaluation is being undertaken. Under these circumstances, it is sometimes necessary to develop models closely paralleling those that have already been developed by the contractor.

Even when models are obtained, the cost is unusually high. Contractors have typically developed their models for internal use, sometimes in a format suitable only for their own computer programs. Before delivery to the USAF, they typically require

more complete validation and documentation. In addition, contractors are financially motivated to retain exclusive control of these models since this makes them a sole source for executing work using the models. All of this places the USAF in a poor negotiating position, resulting in a high cost for obtaining models during the operational part of the aircraft life cycle.

Appropriately, some USAF organizations (particularly certain ALCs) are "gearing up" to become even more involved in FE models. This will result in even more demand for contractor-developed models, especially as newer vintage aircraft that have been designed using FE methods come on-line.

5.2   FE Model Usage With an FEMC

With an FEMC, the way of "doing business" could and should change dramatically. Arrangements for delivery of models should be made during the stage where competition still exists for the airframe contract. With a pre-planned modeling hierarchy and documentation, the cost to the contractor would be less than after-the-fact documentation. Obviously, the contractor would be motivated to deliver these models at the lowest possible cost, to enhance his competitive position for the airframe contract.

Delivery of every FE model developed by the contractor probably should not be required. For a sophisticated aircraft, the number of FE models for all purposes would likely total more than 100. At least initially, models of the entire aircraft (global models) should be required, as well as similar models of each major subassembly, such as wings. A systematic procedure for updating these deliveries should be put into place. This would include requirements for new deliveries for any new derivative or major modification. For models other than those delivered, a cataloging of all models should be furnished to the FEMC.

The result of the above approach would be immediate availability of the most frequently needed models to USAF engineers, without the extra expense of processing numerous models that are not likely to be used. The existence of these undelivered models would be known, and they could be acquired in the same manner that models are acquired today.

5.3 Qualitative Benefits

A number of qualitative or semi-quantitative benefits would derive immediately from a systematic acquisition of FE models from contractors. These benefits would be enhanced and still other benefits would derive from accomplishing this through an FEMC.

Better FE models, hence better products, could be expected from a contractor who is aware that the work may be closely scrutinized by the customer. Improved analysis capabilities are likely to result in more cost-effective testing. For example, better analysis could result in enveloping several load conditions in a single test or eliminating certain test conditions completely. Once testing is completed, the results would be better understood when better models, reviewed by USAF engineers, are available.

Once models are in possession of the USAF, work that could previously be done only by the airframe contractor could now be done by other contractors. This would enhance competitiveness in the procurement of special-purpose analyses.

A centralized approach, such as the FEMC, would reduce equipment and software costs needed for model storage, since such facilities would not need to be duplicated for each user. Development of software used to convert, reduce, or combine models could also be specialized to this location. A wide selection of models would eventually be available at the FEMC, which could be used to assess and validate new research tools.

An extremely valuable side benefit could result from the entire process. The USAF could negotiate a model delivery schedule that supports formal design review activities. In the hands of qualified USAF personnel, these models (including their output) could be used to uncover design problems that may not otherwise surface until years downstream. The same kind of review process could result in a reduction of test requirements with the attendant cost savings.

5.4 Quantitative Benefits

Benefits that would be derived from an FEMC are difficult to quantify, but several sources of quantitative benefit can be identified. These include:

1. Savings in procurement of FE models.

2. Expected savings by increase in aircraft reliability (decreased attrition).

3. Expected savings from increased aircraft utilization (less down time).

4. Expected value in prolonging the life of the fleet.

Some crude estimates for each of these will be given, but all of the figures should be regarded as highly uncertain. In constructing estimates, 20 years is taken as the life of a typical fleet of aircraft.

For estimating FE model procurement savings, it is assumed that, over the next 20 years, most or all of the fleets would be aggressively analyzed by USAF personnel. The manner in which the most active ALC personnel are pursuing analysis of their fleet is taken as a measure of aggressive analysis. There does appear to be a trend toward this as a norm by others at the same ALC and by personnel at other ALCs. In any event, this type of aggressive approach will be quite advisable for future aircraft fleets.

From on-site interviews, it appears that $500,000 to $1,500,000 per fleet is a credible range of expenditure for static stress models for an aggressive analysis program. If $1,000,000 is typical for static models, $500,000 may be credible for dynamic models and $500,000 for all other types. Thus, $2,000,000 (today's dollars) in FE model costs for a future airplane fleet should not be regarded as unusual. From the collection of survey responses, it appears that there are about 30 fleets of aircraft in the USAF inventory. If the life of a fleet is about 20 years, this implies that about 30 fleets x $2,000,000 per fleet ÷ 20 years, or $3,000,000 per year, may be a credible estimate of USAF acquisition costs for future FE models under today's practices. It should be easily possible to save half this amount, or $1,500,000 per year, by procuring models during the competitive phase of the aircraft life cycle (see Section 5.2) under the auspices of an FEMC.

With the staffing, equipment, and software outlined in Section 4, an annual cost of less than $1,000,000 is anticipated to operate the FEMC. Thus, the savings in FE model procurement costs alone is expected to more than offset the cost of operating the FEMC.

The expected savings by increase in reliability (decreased attrition) is even more difficult to estimate. Analysis of USAF cost data [2] for ASC and 5 fleets indicates that the USAF probably spends about $17 billion per year for designing, building, and initial provisioning of its inventory of aircraft. A reasonable estimate of attrition over the life of a fleet may be about 1 percent, indicating about a $170 million loss to attrition per year. If improved and more timely structural analysis could save only 1 percent of this attrition, or, an expected $1.7 million per year in attrition costs, could be saved.

At about $17 billion per year in acquisition costs and more than $15 billion per year in operation, the USAF spends at least $88 million per day to keep its inventory in readiness. If it is assumed that the average fleet of aircraft will have one grounding due to structural problems in its 20-year lifetime and that more timely FE analysis can save only one day of the grounding, the expected annual savings is $88 mil/20 or $4.4 million.

If the life of only one fleet out of the 5 aircraft fleets analyzed could be extended only one year by practices resulting from better FE analysis, the expected value would be dramatic, amounting to about $1.5 billion, which would be about $75 million per year when spread over 20 years.

All of the numbers cited above should be regarded as highly uncertain. However, if they are at all representative, there is much to be gained by improving USAF access to FE models. To argue otherwise, a case would need to be made that a major change in the way a critical function is performed would have virtually no effect on attrition, downtime, or fleet lifetime. An FEMC is an excellent way to achieve enhanced FE model usage. The cost is insignificant when compared to any reasonable estimate of expected benefits.

Statistical decision theory is a recognized method for analyzing alternative courses of action under conditions of uncertainty [3]. Such a method could be applied

to the decision of whether an FEMC is advisable. A rudimentary development of this approach is given in Appendix C.

Section 6
APPROACH FOR FURTHER DEVELOPMENT

There is no question that an FEMC approach for USAF FE models is technically feasible. A number of combinations of software and hardware could perform the required functions. The requisite technical knowledge exists to properly operate such a center.

The benefits from the center are likely to far outweigh the cost. There is likely to even be a near-term savings in FE model procurement costs.

The remaining unknown is whether the FEMC, the FE model users, the SPOs and the airframe contractors will fulfill the required roles in a manner that will allow the center to function from a logistical standpoint. A Phase II SBIR contract should be used to set up a pilot operation to demonstrate the logistical feasibility.

6.1 Overview of Approach

Under a Phase II SBIR contract, Failure Analysis Associates® would set up a pilot FEMC at its Palo Alto facility. This would be accomplished by existing staff on existing computer facilities (with, perhaps, some enhancements). One fighter aircraft would be selected as an example system. The pilot center would demonstrate that all planned functions of the FEMC could be performed for the example system. A steering committee of USAF personnel would be formed to monitor the activity. A subcontract would be awarded to obtain assistance and models from the example system airframe contractor.

6.2 Project Team

The SBIR Phase II contract principal investigator would also function as the pilot FEMC manager. One FE-oriented senior engineer and one programmer/technician would be assigned full-time to the pilot center. Secretarial assistance and other support would be provided by existing Failure Analysis Associates' staff. A particular area in a secure part of the Palo Alto facility would be set aside to house the project team.

6.3 Steering Committee

A Steering Committee of affected USAF personnel should be formulated. It should be chaired by the AFWAL/FIBRA Phase II SBIR project engineer or his designee. There should be at least one representative each from ASD, the ALCs, and the SPO for the example aircraft. Committee members should cover a wide range of static, DTA, dynamic, aeroelastic, and other technical skills to be serviced by the FEMC. There should be regular meetings between the principal investigator, the committee, and the example aircraft airframe contractor.

6.4 Pilot Center Activities

The pilot FEMC should proceed immediately to select specific software and hardware enhancements that are essential for operation of the center. During the same time, discussions should be held with the AFWAL project engineer, ALC, ASD, and the SPOs to identify candidate example aircraft. Once candidates have been identified, the FEMC should enter into discussions and subsequent negotiations with airframe contractors to secure the most cost-effective subcontracting arrangement (of course, with whatever USAF approvals may be required).

A sufficient number of models should be secured to exercise all of the intended functions of the FEMC, as outlined in Section 4. This would include tying at least one ALC and one or more WPAFB users to the system. Pilot FEMC personnel should exercise all of the models and software in the same manner as intended later for the fully-operational FEMC.

Once the technical and logistical feasibility has been thoroughly demonstrated, the FEMC contractor should develop a comprehensive plan for the permanent center. This would include staffing plans, hardware requirements, software requirements, model procurement budgets, and identification of likely funding sources (i.e., paying users). The FEMC should plan and carry out thorough indoctrination programs for all interested parties. If equipment funding is available through the SBIR contract or from other sources, the Phase II contractors should set up the permanent FEMC at a site designated by the USAF.

Section 7
CONCLUSIONS

1. A USAF finite element model center (FEMC) is technically feasible.

2. An FEMC is likely to be cost-effective. It has the potential to provide enormous benefits compared to its cost.

3. Some potential users are skeptical about the utility of an FEMC, with valid reasons. The FEMC structure should be influenced by these concerns.

4. There is currently considerable variation in FE model usage from one ALC to another, but all of the centers appear to be moving toward the greater usage now in place at Warner Robins and Sacramento.

5. Access by the USAF to contractor-developed FE models is extremely limited. When access is gained, it is usually at high cost.

6. FE model usage at the ALCs is dominated by static and DTA analysis. Some dynamic modeling is being done at other installations.

7. MSC NASTRAN and COSMIC NASTRAN dominate as the FE software in use by the USAF.

8. Computer usage in the USAF for FE analysis is dominated by VAX systems.

9. An FEMC would contain valuable USAF aircraft information that must be kept secure. Access to this data can be controlled and models distributed on a need-to-know basis.

Section 8
RECOMMENDATIONS

1. Logistical feasibility of a finite element model center (FEMC) should be demonstrated by a pilot FEMC established under a Phase II SBIR contract.

2. A Steering Committee consisting of representatives from affected USAF organizations should monitor the pilot center operation.

3. Once feasibility is demonstrated, a permanent FEMC should be established.

REFERENCES

1. Thomas, J. M. and Hanagud, S. V., "The Use of Subjective Expert Opinions in Cost-Optimum Design of Aerospace Structures," AIAA Thirteenth Aerospace Sciences Meeting, Pasadena, CA, 1975.

2. Data Book, Management Analysis Group ASD/ACEM, July 1987.

3. Thomas, J. M. and Hanagud, S. V., "Reliability-Based Econometrics of Aerospace Structural Systems: Design Criteria and Test Options," National Aeronautics and Space Administration, TND-7646, 1974.

APPENDIX A

Failure
Analysis
Associates ®

Dr. Jerrell M. Thomas
Vice President

ENGINEERING AND SCIENTIFIC SERVICES
2225 EAST BAYSHORE ROAD. P O BOX 51470
PALO ALTO. CALIFORNIA 94303 (415) 856-9400 TELEX 704216

October 6, 1987

Dear Mr.

Failure Analysis Associates® is under Contract to AFWAL to establish the feasibility of a USAF-wide data base of finite element models for the supportability of the structures of USAF aircraft. Our contract monitor is Dr. Vipperla Venkayya, (513) 255-6992.

Dr. Venkayya has identified you as a potential user of finite element model data bases. Since we want the data base to be of maximum utility to its users, we are conducting a simple survey to help us characterize potential uses of the data base. If you would take the time to complete the enclosed survey forms, it would be of great benefit to the porject. For maximum utility in distributing the work load to the most appropriate persons at your installation, the forms have been designed to be split out by aircraft and by analysis discipline. Would you please assist us in making the survey a success? Please mail your completed survey in the enclosed envelope to:

> Dr. Jerrell M. Thomas
> Failure Analysis Associates
> 2225 E. Bayshore Road
> Palo Alto, CA 94303

A reply by October 20, 1987 would be greatly appreciated.

I anticipate a follow-up visit to selected installations during November. We greatly appreciate this opportunity to interact with USAF finite element model users.

Sincerely,

Jerrell M. Thomas, Ph.D., P.E.
Vice President and Principal Engineer

JMT/bjh

Enclosure

SURVEY INSTRUCTIONS
United States Air Force Finite Element Model Uses

Failure Analysis Associates® is assisting AFWAL in establishing the feasibility of a USAF-wide data base of finite element models for the supportability of the structures of USAF aircraft. Results of this survey will assist us in characterizing needs of potential data base users. A separate sheet should be used for each aircraft and for each specialty (e.g., static analysis).

Finite Element Model User: This entry should reveal the installation (e.g., Warner Robins Air Force Base), organization (e.g., WRALC/MMSR-1), and individual contact at the installation who could answer follow-up telephone questions on this sheet.

Current Aircraft: Enter the name (e.g., F111) and type (e.g., Fighter) of the aircraft for which this sheet is being filled out. Also enter any special structural characteristics (e.g., swing wing; composite tail structure).

<div align="center">or</div>

Anticipated Future Aircraft: Enter the same type of information for aircraft that could foreseeably be assigned to your installation.

Model Types: This information has already been entered. There may be several entries for each model type. Please feel free to add other model types if we have missed some.

Current Usage: Enter information on finite element models used during the past few years at your installation. This section is not applicable to Anticipated Future Aircraft.

Desired Usage: Enter information on the software, computers, and uses that you believe would be beneficial at your installation. For Current Aircraft, this could be additional uses that you would want to pursue if models were available through a USAF data base. For Anticipated Future Aircraft, enter projected usage assuming that such a data base is avialable to you.

Model Source: Enter the source of your model (e.g., purchased from contractor: internally developed).

Software: Enter the name of the computer code (e.g., Cosmic NASTRAN; ANSYS) for each use. Also enter names of pre- and post-processors.

Computer: Enter the name of the computer (e.g., VAX 11/785) for each use.

Summary of Model and Uses: Enter information about the model scope (e.g., complete aircraft; wing), model size, and uses (e.g., investigate cracks: analyze design modification).

SURVEY OF AIR FORCE FINITE ELEMENT MODEL USAGE

Finite Element Model User: _____

Current Aircraft: _____ Installation _____ Organization _____ Contact (Name, telephone)

Name _____ Type _____ Special Structural Characteristics

Anticipated Future Aircraft: _____ Name _____ Type _____ Special Structural Characteristics

Model Types	Current Usage				Desired Usage			
	Model Source	Software	Computer	Summary of Model and Uses		Software	Computer	Summary of Uses
Static Analysis								
A. Stress Analysis								
B. Damage Tolerance & Durability								

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SURVEY OF AIR FORCE FINITE ELEMENT MODEL USAGE

Finite Element Model User:

Current Aircraft:	Installation	Organization	Contact (Name, telephone)
	Name	Type	Special Structural Characteristics
Anticipated Future Aircraft:	Name	Type	Special Structural Characteristics

Model Types	Current Usage				Desired Usage		
	Model Source	Software	Computer	Summary of Model and Uses	Software	Computer	Summary of Uses
Heat Transfer Analysis							
A. Linear Steady State							
B. Linear Transient							
C. Nonlinear Steady State							
D. Nonlinear Transient							

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SURVEY OF AIR FORCE FINITE ELEMENT MODEL USAGE

Finite Element Model User: _____

Current Aircraft: _____

Anticipated Future Aircraft: _____

	Installation	Organization	Contact (Name, telephone)
Name	Type		Special Structural Characteristics
Name	Type		Special Structural Characteristics

Model Types	Current Usage				Desired Usage		
	Model Source	Software	Computer	Summary of Model and Uses	Software	Computer	Summary of Uses
Aeroelastic Analysis							

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SURVEY OF AIR FORCE FINITE ELEMENT MODEL USAGE

Finite Element Model User: _____

Current Aircraft: _____

Anticipated Future Aircraft: _____

Installation	Organization	Contact (Name, telephone)
Name	Type	Special Structural Characteristics
Name	Type	Special Structural Characteristics

Model Types		Current Usage			Desired Usage		
	Model Source	Software	Computer	Summary of Model and Uses	Software	Computer	Summary of Uses
Acoustic Cavity Analysis							

A - 8

List of Contacts for Survey

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Wright Patterson AFB, OH		
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AMDA	Lloyd Matson	(513) 257-2550
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AMDA	Lt. Brandy Powell	(513) 257-2550
McClellan AFB, CA		
MMKRL	Sal Alestra	(916) 924-3719
MMSRC	Rob Bennett	(916) 643-5300
Eglin AFB, FL		
TYE	Ben Shirley	(904) 882-3017
Robins AFB, GA		
MMEMD	Gary Chamberlain	(912) 926-2525
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APPENDIX B

DATA ITEM DESCRIPTIONS

APPENDIX B
Data Item Descriptions

The information presented here is a minimal modification of the Data Item Description: "Data for Finite Element Models of Aerospace Structures" (DD Form 1664, Item 10). The document describes the data elements and the format of the finite element models of aerospace structures to be delivered to the Air Force. This data will be used to verify the contractor's structural analysis and/or to determine the effects of future modifications (or changes) to the structure or its operational conditions. It should be noted that not all the data items are applicable to every system. Applicable items will be identified on a CDRL (DD Form 1423).

10   PREPARATION INSTRUCTIONS

10.1 General Requirements

The finite element data supplied in response to the CDRL item must accompany a problem narrative. This narrative must include the following items:

- Configuration version.

- Identification of the documents and/or drawings from which the model was generated. Copies of these documents must be provided if they are not available to the government.

- A key diagram showing the location of the component being modeled in relation to the rest of the structure.

- A brief description of the physical phenomena being modeled.

- A discussion on the coarseness/fineness of the grid selected, along with a justification for the choice.

- A rational explanation for the elements selected for the model.

- An explanation of the boundary conditions, including references to other finite element models where necessary.

- Materials - Identification of the Mil Standard from which the mechanical properties were derived. Reasons for any deviations from the standard properties.

- A complete description of the flight maneuvers for which the loading conditions are attributed, and an explanation of the basis for loads used (e.g., type of test or analysis).

- Planform used for aerodynamic analyses showing all important dimensions.

10.2 Analysis Data Requirements

The finite element analysis models are classified into the following five categories:

    I.   Static Analysis Models
    II.   Dynamic Analysis Models
    III. Aeroelastic Analysis Models
    IV. Heat Transfer Analysis Models
    V.   Acoustic Cavity Analysis Models.

The CDRL will call for the specific models required.

10.2.1 Static Analysis Model Requirements

A static analysis basically requires a good stiffness representation. However, when gravity loading or inertial relief conditions are specified, a good mass representation is also required. This mass representation must include both structural and nonstructural mass distributions. The finite element models for static analysis must consist of the following items as a minimum.

(i)   Geometry (as appropriate)

    Grid Point Coordinates
    Element Types
    Element Connections
    Coordinate Systems.

(ii)   Element Properties (as appropriate)

    Thicknesses
    Cross-Sectional Areas
    Moments of Inertias
    Torsional Constants

Fiber Orientations
Other properties as required for special elements.

(iii) Material Properties, Principal Material Directions, and Allowables (as appropriate)

Isotropic
Orthotropic
Anisotropic
Fiber Reinforced Composites
Temperature Dependent Properties
Stress Dependent Properties
Thermal Properties
Damping Properties
Other properties as required for special problems.

(iv) Boundary Conditions (as appropriate)

Single Point Constraints
Multipoint Constraints
Partitioning for Reduction or Substructuring.

(v) Loading (as appropriate)

Static Loads - Point and Distributed
Gravity Loads
Thermal Loads
Centrifugal Loads
Other loading conditions as required for special simulations.

For buckling or nonlinear analysis, additional information is required on the following items:

- How the nonlinear matrices are derived.

- The method of solution for the nonlinear problem.

- A description of the method in the case of an eigenvalue analysis.

10.2.2 Dynamic Analysis Models

The dynamic analysis models require (i) geometry, (ii) element properties, (iii) material properties, and (iv) boundary conditions, as described for the static case. In addition, an accurate non-structural mass and damping representation is required. Generally, five types of dynamic analysis are contemplated:

- Normal Modes Analysis

- Complex Eigenvalue Analysis

- Frequency Response Analysis

- Transient Response Analysis

- Random Response Analysis

In the first two cases, only the method of eigenvalue analysis and the frequency (modes) range of interest need be specified. For frequency response analysis, the frequencies of interest must be specified. For transient response, the dynamic load must be defined as a function of time, and the solution procedure used should be defined. For random response analysis, the statistical nature of the input (such as PSD, Auto Correlation) and the statistical quantities of the output desired must be specified. In addition, all the information on dynamic reduction and/or modal reduction must be specified. The eigenvalue extraction method should be defined.

10.2.3 Aeroelastic Models

An aeroelastic analysis requires mathematical models of the structure and the aerodynamics. The structure is generally represented by finite element models (FEM). The requirements for the structures models are as specified under static and dynamic analysis. They include mass, stiffness, and damping representation. Both structural and non-structural mass distributions shall be included in the mass model. The aerodynamic modes are generally based on paneling or equivalent methods. The requirements of the aerodynamic models are those of the panel geometry which cover all the lifting surfaces, including the control surfaces, the empennage (horizontal and vertical tails), and canard surfaces. The fuselage slender body and interference panels shall be modeled to represent the flow-field adequately. The altitude (air density), mach number, and other relevant aerodynamic parameters must be specified. The details of the aerodynamic theory and the limits of its validity must be clearly defined. In addition, data for the force and displacement transformations from the structural grid to the aerodynamic grid (and vice versa) shall be included in the aeroelastic models.

Two types of aeroelastic analysis are contemplated. Both deal with the phenomenon of aeroelastic stability. The real eigenvalue analysis is the basis for determining the static aeroelastic stability. There are a number of methods for determining dynamic aeroelastic stability (flutter analysis), and the details of the method (references) and the necessary data shall be provided with the models. Flutter analysis is generally an iterative process and can also involve more than one flutter mechanism. There are often special techniques associated with the flutter analysis, and they can be defined in terms of the ranges of the aerodynamic parameters. Such data shall be included in the aeroelastic models. In addition, provisions must be made to include the effects of the rigid body modes on the flutter model (body freedom flutter). If it is anticipated that these models will be used for aeroservoelastic analysis, then the data shall be provided for a state space formulation. Also, sensor actuator locations and their range of operation and/or limitations shall be included in the data. In addition, a flight control system block diagram shall be provided with sufficient information to define all transfer functions and gains using S-domain variables for analog systems or Z-domain variables for digital systems. The units of all parameters shall be provided.

10.2.4   Heat Transfer Analysis Models

There are three elements to heat transfer models: the heat conducting medium, the boundary conditions, and the heat sources and/or sinks. The data requirements of the heat conducting medium are similar to those defined for static and dynamic analysis. For instance, the geometry definition includes the grid point coordinates, element types, element connections, and coordinate systems. Elements can be classified into volume heat conduction and surface elements. The surface elements are used to model a prescribed heat flux, a convective flux due to the difference between the surface temperature and the recovery temperature or local ambient temperature, and radiation heat exchange. Appropriate material properties, including heat capacitance and conductances, single-point and multi-point boundary conditions, and description of the heat sources (applied forces) have a similar correspondence in the static and/or dynamic analysis. The surface heat convection or radiation details shall be provided (through surface elements), as appropriate. The response variables in heat transfer analysis are generally grid point temperatures or the temperature gradients and heat fluxes within the volume heat conduction elements and the heat flow into the surface elements. Four types of heat transfer analysis are contemplated:

(i)   Linear Steady-State Response Analysis

(ii)   Linear Transient Response Analysis

(iii)   Nonlinear Steady-State Response Analysis

(iv)   Nonlinear Transient Response Analysis.

It is often necessary to adopt special techniques for obtaining stable solutions, particularly in the last two cases. The data pertaining to these special techniques and the limitations of the nonlinear algorithms shall be fully identified.

10.2.5   Acoustic Cavity Analysis Models

Basically, there are three elements in acoustic cavity analysis models: the acoustic medium, the boundaries, and the sources of excitation. The acoustic medium model shall consist of grid points and acoustic elements connecting these grid points. The response variables are generally the pressure levels and the gradients of the pressures (with respect to the spatial variables) at the grid points. So, for a general three-dimensional acoustic analysis, there will be four degrees of freedom per node (corresponding to four response variables) in an acoustic medium model. The properties of the acoustic medium can vary with the temperature and pressure distribution and density. The boundaries of the acoustic model can be solid walls, flexible walls, openings in the walls, and walls with acoustic material which can be represented as a complex acoustic impedance. For complicated boundary conditions, separate finite element models may be necessary in order to derive the boundary conditions for the acoustic model. These finite element models are based on solid mechanics, and their data requirements are similar to those described for the static and dynamic analysis earlier. The acoustic excitation source model shall have information on the spatial distribution and the statistical properties (in terms of the frequency content) of the noise. For a deterministic case, however, definition of the forcing function includes the magnitude, phasing, and frequency along with the spatial distribution. The acoustic excitation is generally given as velocity or pressure applied to the medium over prescribed surfaces or at grid points. If the disturbance is from mechanical sources, separate finite element models of the sources shall be supplied as required. These models are also generally solid mechanics models, and their

requirements are similar to static and dynamic analysis models. Generally, three types of acoustic analysis are contemplated:

- Eigenvalue Analysis

- Steady-State Analysis

- Nonlinear Analysis.

In the eigenvalue analysis, the acoustic natural frequencies and mode shapes are determined. The purpose is to compare the natural frequencies of the cavity with those of the forcing function and estimate the resonance effects and to compare the natural frequencies to the resonant frequencies of any structure which may be placed in the cavity. This analysis provides useful information for design changes in the cavity, either by altering the overall dimensions or by introducing noise suppression mechanisms, such as baffles, or by adding noise suppression material to introduce acoustic wall impedance. This analysis does not require explicit definition of the forcing function. The steady-state solution gives the response of the cavity to a given excitation. This analysis can be in the time or frequency domain. The nonlinear analysis involves an iterative solution when the properties of either the cavity or the acoustic medium vary significantly with the pressure levels and/or temperature.

10.3 Other Requirements

The input data for all the finite element models must be provided in a format compatible with the latest government version of COSMIC/NASTRAN or the latest release of MSC NASTRAN. If the original analysis was made with another finite element program, the data shall be converted to one of the approved formats. If NASTRAN does not have compatible elements or capability, the elements that are most appropriate must be identified and projections must be provided on the expected differences.

In addition to the input data, a summary of output results (such as deflections, stresses, frequencies, etc., at critical areas) shall be provided for future validation of the models, along with a brief description of how these results were used to satisfy a specific design criteria. A set of undeformed and deformed plots of the structure shall

be provided with all the finite element models. Contour plots of stress or temperature for the most critical load steps or times should also be included.

APPENDIX C

STATISTICAL DECISION THEORY FRAMEWORK

APPENDIX C
Statistical Decision Theory Framework

Statistical decision theory provides a formalized framework for determining optimum decisions under conditions of uncertainty. Therefore, the fundamental concepts of statistical decision theory will be briefly and informally outlined. Benjamin and Cornell [C.1] have given a thorough treatment of statistical decision theory as applied to engineering problems.

The decision making process, illustrated graphically in Figure C.1, is formulated as the process of choosing an "action" from the set of alternatives a_1, a_2, ... a_n. Consequences of the action will depend on some variables which are not known with certainty. These variables are termed the "state of nature," denoted by θ_{ij}. Value or utility is the measure of the consequences of an action-state pair, denoted by $u(a_j, \theta_{ij})$.

In statistical decision theory, it is shown that the decision to pursue a particular course of action should be based on selecting the action with highest expected utility (or alternatively, the lowest expected cost), where expected utility is given by:

$$E\ [u/a_i] = \sum P_{\theta ij}\ u(a_i, \theta_{ij}) \tag{C-1}$$

where $P_{\theta ij}$ is the probability that the state of nature will be θ_{ij}. In this example, θ_{ij} was assumed to be probabilistically described by a discrete probability mass function. For continuous probability density functions, Eq. (C-1) is easily generalized.

A rudimentary decision tree for evaluating the advisability of establishing an FEMC against other alternatives is illustrated in Figure C.2. Some elements of the decision tree are explained in Figure C.3. Analysis of the decision tree is not carried out, but the analysis method that would be used is represented by Eq. (C-1).
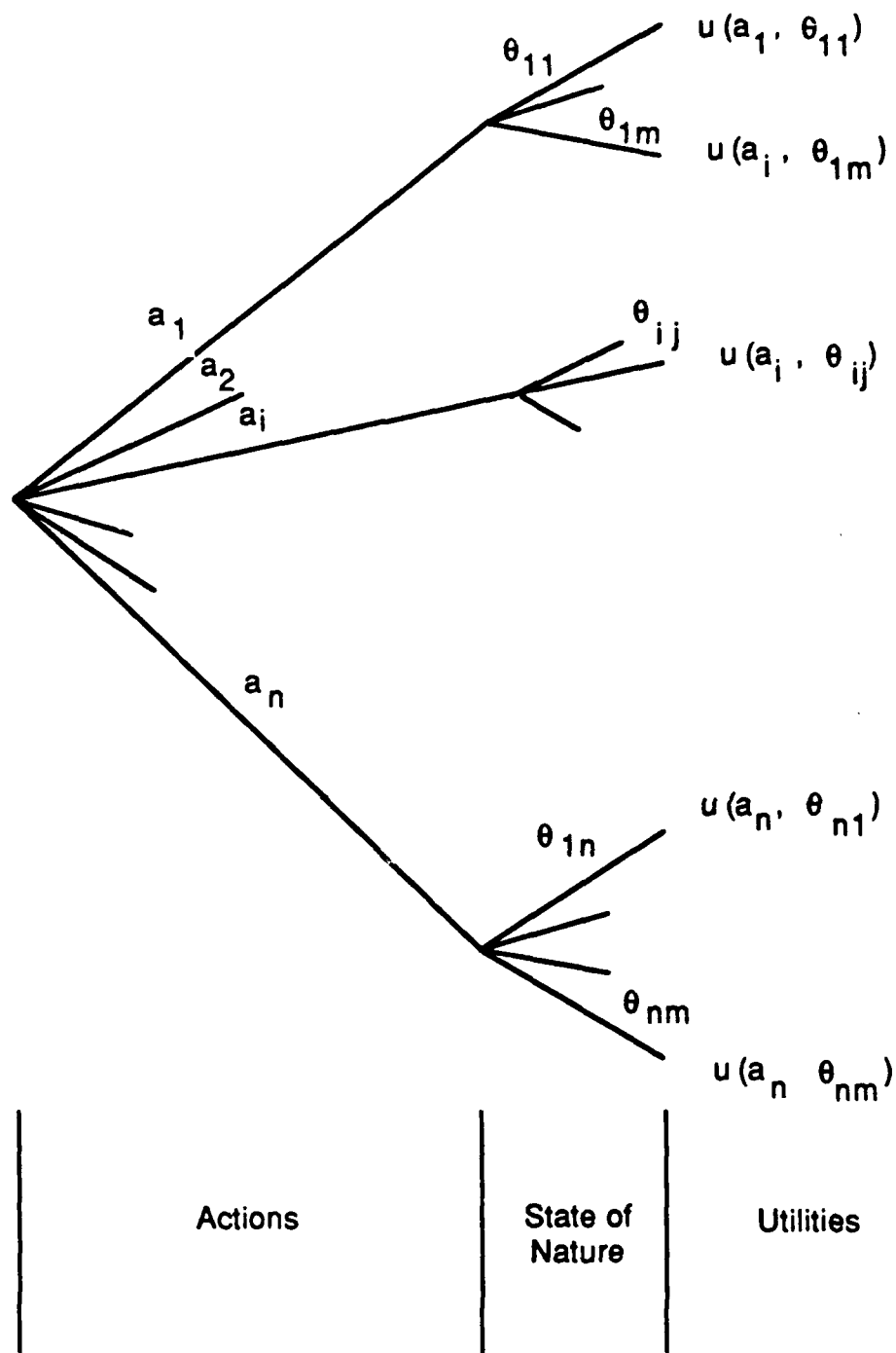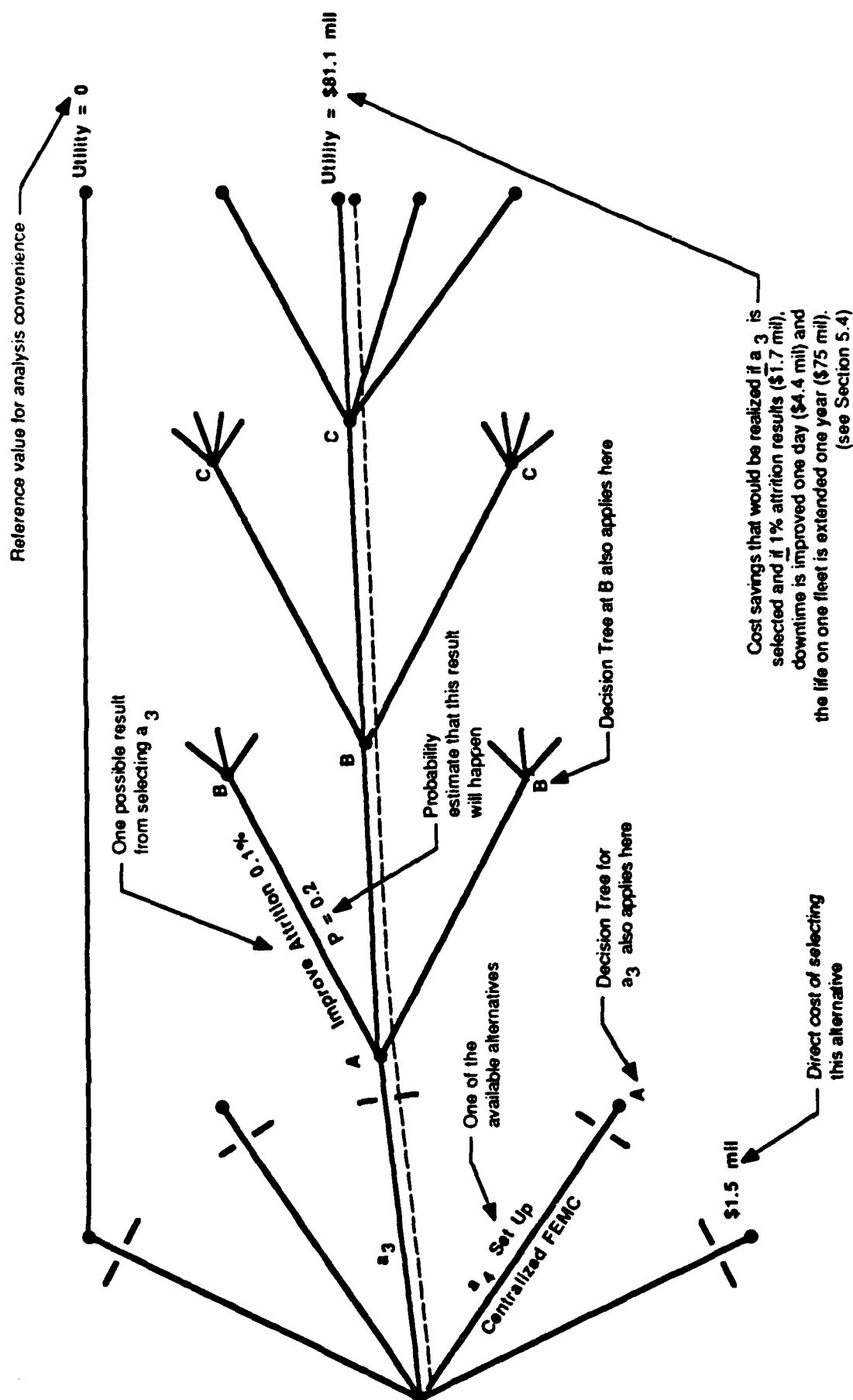
Figure C.1. Decision Tree

Figure C.2. Rudimentary Decision Tree for FEMC Alternatives

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Figure C.3. Explanation of Decision Tree Elements

Reference value for analysis convenience

Utility = 0

Utility = $81.1 mil

One possible result from selecting a₃

Improve Attrition 0.1%

P = 0.2

Probability estimate that this result will happen

Decision Tree at B also applies here

One of the available alternatives

Set Up

Decision Tree for a₃ also applies here

Centralized FEMC

Direct cost of selecting this alternative

$1.5 mil

a₃

a₄

Cost savings that would be realized if a₃ is selected and if 1% attrition results ($1.7 mil), downtime is improved one day ($4.4 mil) and the life on one fleet is extended one year ($75 mil). (see Section 5.4)

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From the authors' experience in analyzing decision trees and the information presented in Section 5.4, the following would result if the analysis were carried out:

1. "Continue current practice" would be far inferior to all the other alternatives.

2. "Acquire FEM through present channels" would be slightly inferior to setting up an FEMC.

3. All of the FEMC alternatives would have equal value. The decision between them should be based on considerations other than expected costs.

If such a decision tree is to be eventually used in making the decision, the tree, the utility estimates, and the probability estimates should all be improved first. It is highly doubtful that the effort to do this would be justified. Given the information in Section 5.4, it is already clear that an FEMC is likely to be highly cost-effective compared to the current practice.

References

C.1 Benjamin, Jack R. and C. Allin Cornell, Probability Statistics and Decision for Civil Engineers, McGraw-Hill Book Company, New York, 1970.

APPENDIX D
CATALOG INFORMATION

APPENDIX D
Catalog Information

Information to be added to the FEMC database for each new model consists of two sections.

I.   Attributes of finite element models to aid in database gauging:

- aircraft name

- aircraft type

- component or subassembly

- analysis type

- analysis subtype

- analysis data

- contractor or USAF center that developed model

- finite element program used

- storage location of model

- model validation state.

II. Discussion of model to help user decide which model shall be requested.

Include explanation of:

- physical phenomenon being modeled

- coarseness/fineness of the grid with the number of elements and sides used

- loading conditions and what flight maneuvers they represent

- analysis approach and solution mechanism

- key results obtained from the model.